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LIFE CYCLE MANAGEMENT

How can a life cycle inventory parametric model streamline life cycle assessment in the wooden pallet sector?

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Abstract

Purpose This study discusses the use of parameterization within the life cycle inventory (LCI) in the wooden pallet sector, in order to test the effectiveness of LCI parametric models to calculate the environmental impacts of similar products. Starting from a single case study, the objectives of this paper are (1) to develop a LCI parametric model adaptable to a range of wooden pallets, (2) to test this model with a reference product (non-reversible pallet with four-way blocks) and (3) to determine numerical correlations between the environmental impacts and the most significant LCI parameters; these correlations can be used to improve the design of new wooden pallets.

Methods The conceptual scheme for defining the model is based on ISO14040-44 standards. First of all, the product system was defined identifying the life cycle of a generic wood pallet, as well as its life cycle stages. A list of independent and dependent parameters was used to describe the LCI flows of a generic wooden pallet. The LCI parametric model was applied to calculate the environmental impacts of the reference product, with regard to a selection of impact categories at midpoint level (climate change, human toxicity, particulate matter formation, agricultural land occupation, fossil depletion). The model was then applied to further 11 wooden pallets belonging to the same category.

Results and discussion The definition of a LCI parametric model based on 31 independent parameters and 21 dependent parameters streamlined the data collection process, as the information required for fulfilling the LCI are standard information about the features of the wooden pallet and its manufacturing process. The contribution analysis on the reference product revealed that the most contributing life cycle stages are wood and nails extraction and manufacturing (positive value of environmental impact) and end-of-life (avoided impact). This result is driven by two parameters: mass of wood and average distance for transport of wood. Based on the results of the application of the LCI parametric model to the identified products, one parameter-based regression and one multiple non-linear regression allowed to define a correlation between the life cycle impact assessment (LCIA) category indicators considered and the most influencing parameters.

Conclusions The definition of LCI parametric model in the wooden pallet sector can effectively be used for calculating the environmental impacts of products with different designs, as well as for obtaining a preliminary estimation of the life cycle environmental impacts of new products.

Keywords Design · Life cycle inventory · Parameterization · Regression · Streamlined LCA · Wooden pallet

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1 Introduction

The woodworking industry plays a significant role in the European context, being a major employer in many of the Member States of the European Union and featuring among the top three industries in Austria, Finland, Portugal and Sweden. The industry covers a wide range of activities, from sawmilling, planning and pressure treating to the production of wood-based panels, veneer and boards, from construction products to joinery and from pallets and packaging to furniture (Beyer et al. 2011). Inside the woodworking industry, wooden packaging is of critical importance since it provides an essential outlet for sawn timber, from small logs and as falling boards from larger logs. The European pallet and packaging industry uses about 20 million m^3 of timber, the equivalent of 350 million pallets, light weight and industrial packaging (European Confederation of Woodworking Industries 2006). In the last several years, there has been an increasing interest in the evaluation of the environmental impacts of wood, which has a potential to be reused many times, providing both material and energy recovery (Hischier et al. 2005). The most prominent tool for the evaluation of the potential environmental impacts connected with a product, process or service, is the life cycle assessment (LCA) methodology. Several LCA studies have recently been carried out in relation to woodworking products such as window frames (Asif et al. 2002), furniture (Taylor and van Langenberg 2003), particle boards (Rivela et al. 2006; Silva et al. 2013) and wood boxes for wine bottle storage (González-García et al. 2011). Even though LCA is a widespread tool in the woodworking industry, very few applications can be found in the wooden packaging sector, despite the fact that this sector holds a significant market share (FAO 2013). Among the existing studies, the focus has been mainly on waste management strategies (Gasol et al. 2008; Ng et al. 2013), as well as the comparison of the environmental performances with competing materials, such as plastics (ERM 2008; Lee and Xu 2004).

Companies within the woodworking industries are mostly small and medium-sized enterprises (SME), with only a few large groups, typically in the softwood sawmill, panel and parquet sectors, operating on a European or global scale (Beyer et al. 2011). As it is widely recognized that LCA methodology is time and resource consuming with particular regard to data collection and data handling (Finnveden et al. 2009; Zamagni et al. 2012), it is even more difficult for SMEs to implement LCA in their daily business practice. In fact, SMEs rarely have the knowledge and resources necessary for implementing LCA; therefore, a priority in the research should be to facilitate the access to reliable, accurate and relevant life cycle information, which can reduce the efforts and time connected for both data acquisition and model development (Baitz et al. 2013). This need has motivated different efforts in the direction of simplifying or accelerating the process of making knowledge available in an easily usable way (Zamagni et al. 2012). A large number of simplified LCA methods have been developed (Baumann and Tillman 2004; Pesonen and Horn 2013). A simplified approach is provided by screening LCA (which is a streamlined application of the LCA methodology) by using generic data, standard modules for transportation or energy production, etc., and followed by a simplified assessment (Curran 2011). As screening LCA is available from readymade databases, there is no need to make new inventory calculations. Furthermore, the significance of the use of proxy indicators, such as the non-renewable fossil Cumulative Energy Demand (CED) for preliminary analysis before starting a full LCA application, has been tested in many industrial sectors (Huijbregts et al. 2006; Niero 2013a; Scipioni et al. 2013). These simplified techniques can be effectively applied for the improvement of existing products or for the comparison of products; however, their effectiveness has not yet been tested with regards to the development of new products. One example, i.e. the Oil Point Method (OPM) based on the combined used of primary energy relationships and process-specific indicators, has shown to be able to perform rough environmental evaluations and support material- and process-related decision-making in the early stages of design (Bey 2000). LCA is in most cases too complex to be integrated as a regular constituent into product development, and its effectiveness as a tool to assess environmental considerations in the product design process has received both support (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2013) and criticism (Millet et al. 2007). Other tools recognized to be useful to simplify and optimize data collection within the life cycle inventory (LCI) step of an LCA study are parametric LCI models (Mueller et al. 2004). Parameterization in the LCI refers to the practice of presenting LCA data using raw data and formulas instead of computed numbers in unit process datasets within databases (Cooper et al. 2012). This technique can indeed be used to define the life cycle inventory of a range of products, when they present similar characteristics. Furthermore, when focusing at the company level, a distinction should be made between operations which are common for all the products and those operations which are specific to particular products. Therefore, companies, particularly SMEs, would benefit from the development of a model based on a defined set of parameters to describe the life cycle inventory and use this model to assess the environmental impacts of products that have similar characteristics.

The main applications of parametric LCI models in the literature refer to the design phase of different products within the mechanical sector, i.e. direct current (DC) motor (Dick et al. 2004), induction motor (Mueller et al. 2004), automotive materials (Geyer 2008), cranes (Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011) and wind energy converters (Zimmermann 2013) and the packaging sector

for vehicle service parts and accessories (Early et al. 2009) as well as beverages packaging (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010). The possibility of implementing parameterization in the LCI has not yet been tested in the wooden packaging literature, particularly with regard to wooden pallet.

Starting from these premises, this research considers a single case study in the wooden pallet sector concerning an Italian company in order to investigate to what extent companies in the wooden pallet sector can benefit from the use of parametric LCI models for evaluating the environmental impacts of similar products and providing a preliminary assessment of the potential environmental impacts of new products before their introduction into the market.

The objectives of this paper are (1) to develop a parametric model describing the life cycle inventory of a range of wooden pallets used as tertiary packaging, (2) to test the effectiveness of the LCI parametric model with a reference product, namely a non-reversible pallet with four-way blocks, and (3) to determine numerical correlations between the environmental impacts and the most significant life cycle inventory parameters, which can be used to design a generic wooden pallet.

2 Materials and methods

2.1 Definition of the LCI parametric model

In order to test the possibility to implement parameterization in the LCI in the wooden pallet sector in accordance with the requirements of the ISO standards (ISO 2006a, b), the procedure proposed in Fig. 1 was followed.

The conceptual scheme is based on the four-step LCA methodology, where the requirements of each step are adapted in order to be used for the product group addressed by the model. The intended product group are pallets, defined as "platforms or trays on which goods may be packed to form unit loads for handling by mechanical devices" (ISO 2013), whose constituent material is wood. Even though a wood pallet is a relatively simple product, there can be a wide range of wooden pallets, which differ from one another in terms of size, number of blocks and deck/bottom boards, type of wood and production processes. The procedure defined in Fig. 1 can be applied by any manufacturing of the wooden pallet; meanwhile, the LCI parametric model here described is tailored to the case study company, which can be considered representative of an average Italian SME manufacturing wooden pallet.

To meet the first objective of the study, the first step was to describe the life cycle of a generic wooden pallet manufactured by the case study company, through the identification of the common aspects in the life cycle of the products and definition of common and optional processes in the manufacturing. This step corresponds to the product system definition as included in the goal and scope definition of an LCA study (ISO 2006a, b). The life cycle of a generic wooden pallet is presented in Fig. 2, which includes the entire stages from raw and auxiliary materials acquisition to the end-of-life, including manufacturing, distribution and use of the product. The raw materials considered are wood (softwood such as pinewood or fir, and hardwood, such as poplar and alder, which is used for the constituting elements of the pallet) and steel nails (smooth, helical or pointless helical, according to their shape). Auxiliary materials are all the materials used for raw materials and final product packaging (plastics and metallic straps, cardboard, labels) and equipment maintenance (lubricant oil). After a temporary storage, raw materials enter the manufacturing process, which includes some operations which are common to all the wooden pallets (cutting and assembly) and some other operations that are optional.

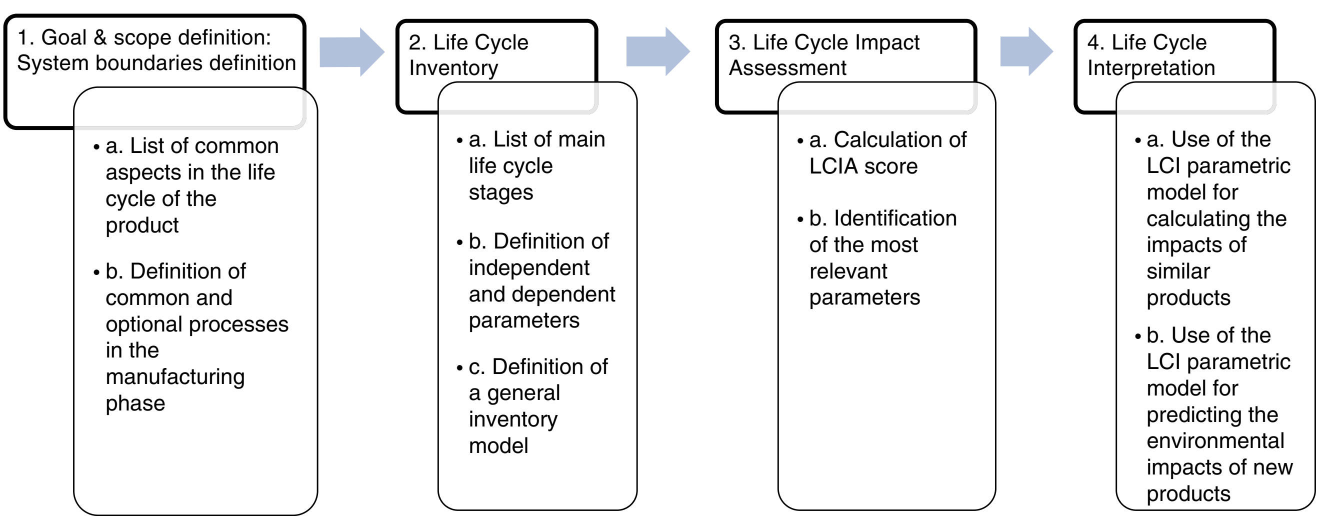

Fig. 1 Conceptual scheme for the definition of a LCI parametric model in the wooden pallet sector according to the 4-steps LCA methodology

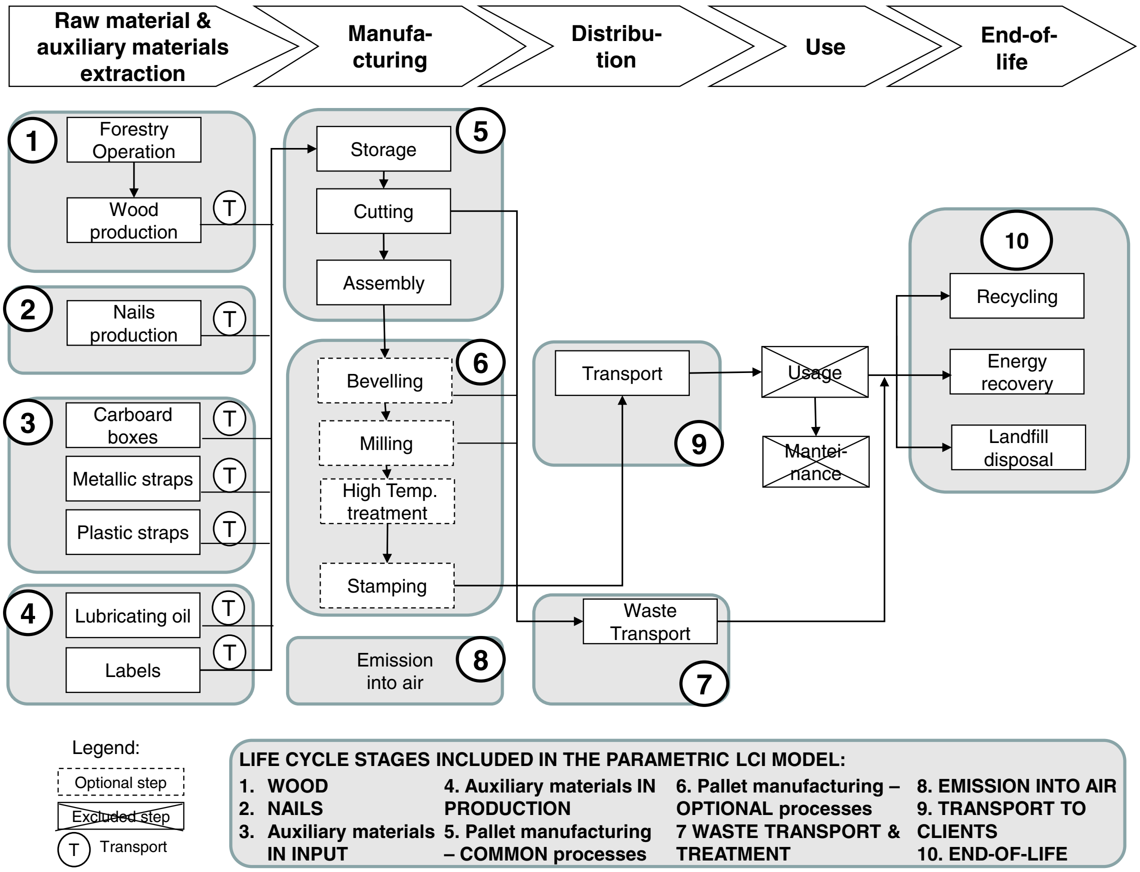

Fig. 2 Definition of the life cycle of a generic wooden pallet manufactured by the case study company with the inclusion of the process units that are common to all the products (*rectangular shape*) and those that are optional (*dashed shape*), as well as the phases left outside the system boundaries (*excluded box*). The correlation between the process units and the life cycle stages included in the parametric LCI model are represented by the *grey boxes* and *numbers*

Optional processes, which may be included or not according to expected final product, are as follows:

- Bevelling, i.e. cutting of the edges of the pallet
- Milling: a superficial treatment using rotary cutters to remove materials from a work piece which advances in a direction at an angle with the axis of the tool
- High-temperature (HT) treatment: the heating of the wood, which must achieve a minimum core temperature of 56 °C for at least 30 min, as phytosanitary treatment
- Stamping: conducted in conjunction with the high-temperature treatment

The use phase and maintenance are excluded from the system boundaries. As mentioned by Ng et al. (2013), the end-user is responsible for maintenance and storage of pallets. Due to various handling scenarios of pallets, these life cycle stages are subject to high variability. Meanwhile, the transport of the final products and waste, as well as the waste treatment and the final end-of-life of the product, is included. For the waste and final product disposal, the recycling process was modelled according to the "system expansion" approach (Frischknecht 2010); therefore, the avoided impacts from primary production were included, considering the following avoided products from the Ecoinvent database (Frischknecht et al. 2005):

- Wood pellets from wood waste from cutting phase (Werner et al. 2007)
- Core board for cardboard (Werner et al. 2007)
- Pig iron for metallic straps (Classen et al. 2009)
- Nylon 66 for plastic straps (Hischier 2007)
- Polypropylene granulate for labels (Hischier 2007)
- Particle board for residual wood (final product) (Werner et al. 2007)

For the recycling of waste and the final product, the system expansion option was adopted, considering the selection efficiency and substitution rates for metals in accordance with Rigamonti et al. (2009), Rigamonti and Grosso (2010) and Lazarevic et al. (2010). For the definition of the end-of-life of the wood pallet, the scenario has been defined following the report of the Italian consortium responsible for the collection, recovery and recycling of wooden packaging (Rilegno 2010):

37 % landfill, 60 % material recycling and 3 % incineration with energy recovery. Therefore, these percentages refer to the whole wooden tertiary packaging or transport packaging sector, where by tertiary packaging we refer to “packaging conceived as to facilitate handling and transport of a number of sales units or grouped packaging in order to prevent physical handling and transport damage” (EC 1994). More than half of the tertiary packaging in Italy consists of wooden pallets, but also wooden industrial packaging, fruits and vegetables packaging and corks are included in the statistics (Rilegno 2010).

Once the process units included in the life cycle of a generic pallet manufactured by the case study company have been defined (steps 1a and 1b in Fig. 1), we grouped them in 10 life cycle stages (step 2a in Fig. 1), which are listed and described in Table 1. Other options for the grouping might have been chosen, but this option was identified as the most representative of the production of the case study company. Furthermore, these 10 life cycle stages reflect the structure of the questionnaire used for primary data collection, which the company was asked to fill in.

For each life cycle stage, we determined the inputs and outputs through the definition of a set of independent parameters and dependent parameters (step 2b in Fig. 1). Independent parameters can be defined with a single value and belong to six different categories which describe characteristics inherent in the products (i.e. number of elements, size of the elements, mass of elements), distance for transport and switches which can be used to include or not optional processes in the manufacturing phase. Among the independent parameters categorized as “others”, the nominal density of the wood (*rho*) and waste fraction during cutting (*waste_c*) was considered as constants, equal to 500 kg/m^3 and 0.03, respectively. Independent parameters represent the required user input to the LCI parametric model and are limited to 31 values, as listed in Table 2. They have been named specifying first the sub-category and then providing an acronym to specify the material or part of the design. Dependent parameters are calculated through mathematical correlations between independent parameters and defined with the same rule of the independent ones (Table 3). For the 21 dependent parameters, a fixed fraction of waste for the milling and beveling phases was considered, equal to 0.005 and 0.002, respectively, and calculated with regard to the amount of wood in the final product (*mass_wood*). Among the dependent parameters, three parameters are particularly relevant, as each life cycle stage refers to one of them (Table 1). They are called “primary parameters”: *mass_wood* (which is the total mass of wood in the final pallet), *mass_nails* (which is the total mass of steel nails in the final pallet) and *mass_pallet* (which is the total mass of the pallet, given by the sum of *mass_wood* and *mass_nails*).

The information required to perform the LCA include independent parameters and consequently dependent parameters, which basically define the material input to the product system. Regarding the energy input, waste fraction and primary emissions into air data were collected for each wooden pallet. The list of the main input and output for the LCI of a generic wooden pallet manufactured by the case study company is presented in Section 2.2.2, with regard to the reference product.

Table 1 Life cycle stages of the wooden pallet considered in the life cycle inventory parametric model describing the life cycle of a generic wooden pallet manufactured by the case study company and definition of the primary parameters connected with each life cycle stage

Life cycle stages	Description of what is included	Primary parameter	Unit
1. Wood	Production and transport of the different wooden components (blocks, stringer boards, deck boards, bottom boards), considering the number of elements included in the final products as well as the EURO class and average load of the truck used for the transport	mass_wood	kg
2. Nails	Production and manufacturing of steel for the different types of nails, as well as the transport of nails supply	mass_nail	kg
3. Auxiliary materials in input	Production and transport of input auxiliary materials (cardboard boxes, metallic and plastics straps)	mass_wood	kg
4. Auxiliary materials in production	Production and transport of auxiliary materials used in the manufacturing phase (lubricating oil, labels)	mass_wood	kg
5. Pallet manufacturing—common processes	Consumption of diesel for fork lifts, diesel combusted in the boiler for the drying phase and electricity consumption (hydropower source) for cutting and assembly phases	mass_wood	kg
6. Pallet manufacturing—optional processes	Consumption of liquefied petroleum gas (LPG) for the industrial furnace during the high temperature (HT) treatment, as well as electricity consumption (hydropower source) for beveling, milling, HT treatment and stamping	mass_wood	kg
7. Waste transport and treatment	Transport and recycling treatment of wood wastes (from cutting, beveling and milling) as well as the transport and recycling of labels and metallic straps	mass_wood	kg
8. Emission into air	Emissions of particulates during the manufacturing phase	mass_wood	kg
9. Transport to clients	Transport to the final customers by truck	mass_pallet	kg
10. End of life	End of life of wood pallet, including the final disposal of wood and nails	mass_pallet	kg

Table 2 List and description of the independent parameters according to the identified sub-categories. The unit of measurement of each parameter is reported in brackets after the name of the parameters

Sub-categories	Parameters	Description
Number of elements	*n_str (−)*	Number of stringer boards
	n_deck_b (−)	Number of deck boards
	n_bottom_b (−)	Number of bottom boards
	n_he_n (−)	Number of helical nails
	n_sm_n (−)	Number of smooth nails
Size of elements	*l_b (m)*	Length of deck and bottom boards
	w_ deck_b (m)	Width of deck boards
	h_ deck_b (m)	Height of deck boards
	w_ bottom_b (m)	Width of bottom boards
	h_ bottom_b (m)	Height of bottom boards
	l_str (m)	Length of stringer boards
	w_str (m)	Width of stringer boards
	h_str (m)	Thickness of stringer boards
	h_bl (m)	Height of blocks
	l_bl (m)	Length of blocks
Distance for transport	*dist_str (km)*	Weighted distance for the transport of stringer boards
	dist_deck_b (km)	Weighted distance for the transport of deck boards
	dist_bottom_b (km)	Weighted distance for the transport of bottom boards
	dist_bl (km)	Weighted distance for the transport of blocks
	dist_nails (km)	Weighted distance for the transport of nails
	dist_client (km)	Weighted distance for the transport to clients
Mass of elements	*mass_he_n (g)*	Mass of 1 helical nail
	mass_sm_n (g)	Mass of 1 smooth nail
	mass_pl_he_n (g)	Mass of 1 pointless helical nail
Switches	*mill*	Switch for milling phase
	bevel	Switch for board beveling phase
	HT	Switch for the high-temperature treatment phase
	stamp	Switch for the stamping phase
Others	*rho* (kg/m^3)	Nominal density of wood
	waste_c (−)	Waste from the cutting phase
	hard_str (−)	Fraction of hardwood in stringer boards

The final outcome of step 2 in Fig. 1 (step 2c) is the definition of a general parametric inventory model of the life cycle of a wooden pallet, covering all relevant processes and stages of a wooden pallet's life cycle, as described by Fig. 2.

The LCI parametric model can be used to calculate the LCI of a wide range of wooden pallets manufactured by the same company. Information needed by the model is, indeed, representative of a range of products having similar characteristics and similar production processes. We applied the LCI model to calculate the environmental impacts of 12 products manufactured by the case study company, belonging to the same category, i.e. one non-reversible pallet with four-way blocks. The list of the independent and dependent parameters for the 12 products considered is presented in Tables 4 and 5, where all products are identified by an alphabetic letter (RP refers to the reference product). This set of wooden pallets represents the core business of the case study company, as well as the most commercially sold products which are representative of the company's broader operations. They differ basically in terms of the following characteristics: size (1.2 m×0.8 m; 1.2 m×1.0 m; 1.0 m×1.0 m; 0.9 m×1.0 m), number of deck boards (five or seven), presence/absence of the high-temperature treatment, type of wood (softwood or hardwood) and inclusion/exclusion of other optional processes. In particular, the inclusion of the high-temperature treatment is connected with the manufacturing of wooden pallet to be sold in the extra European market, with reference to the standard ISPM 15 (FAO 2009). This standard describes internationally accepted measures that may be applied to wood packaging material by all countries to reduce significantly the risk of introduction and spread of most quarantine pests that may be associated with that material, including thermal treatment.

Table 3 List, description and calculation formula for the dependent parameters according to the identified sub-categories. The unit of measurement of each parameter is reported in brackets after the name of the parameters

Sub-categories	Parameters	Description	Formula
Number of elements	*n_bl (−)*	Number of blocks	= *n_str * n_bottom_b*
	n_pl_he_n (−)	Number of pointless helical nails	= *n_he*
Size of elements	*w_bl (m)*	Width of blocks	= *w_bottom_b*
	vol_deck_b (m^3)	Volume of deck boards	= *w_deck_b * l_b * h_deck_b*
	vol_bottom_b (m^3)	Volume of bottom boards	= *w_bottom_b * l_b * h_bottom_b*
	vol_bl (m^3)	Volume of blocks	= *w_bl * l_bl * h_bl*
	vol_str (m^3)	Volume of stringer boards	= *w_str * l_str * h_str*
Mass of elements	*mass_deck_b (kg)*	Mass of deck boards	= *vol_deck_b * rho*
	mass_bottom_b (kg)	Mass of bottom boards	= *vol_bottom_b * rho*
	mass_b_tot (kg)	Total mass of boards	= *n_deck_b * mass_deck_b+ n_bottom_b * mass_bottom_b*
	mass_bl (kg)	Mass of blocks	= *vol_bl * rho*
	mass_bl_tot (kg)	Total mass of blocks	= *n_bl * mass_bl*
	mass_str (kg)	Mass of stringer boards	= *vol_str * rho*
	mass_str_tot (kg)	Total mass of stringer boards	= *n_str * mass_str*
	mass_nails (kg)	Mass of nails	= *n_he_n * mass_he_n+ n_sm_n * mass_sm_n+ n_pl_el_n *mass_pl_el_n*
	mass_wood (kg)	Mass of wood	= *mass_bl_tot + mass_str_tot+ mass_b_tot*
	mass_pallet (kg)	Mass of pallet	= *mass_wood + mass_nails*
Distance for transport	*dist_pond (km)*	Average distance weight of wood	= *[dist_bl*mass_bl_tot + (dist_deck_b + dist_bottom_b)*mass_b_tot + dist_str*mass_str_tot]/ mass_wood*
Others	*waste_m* (−)	Waste from the milling phase	= *0.05 * mill*
	waste_b (−)	Waste from the beveling phase	= *0.02 * bevel*
	waste_tot (−)	Total waste	= *waste_m + waste_b + waste_c*

2.2 Validation of the LCI parametric model

2.2.1 Goal and scope definition

With reference to the second objective, the goal of the LCA study was to define the environmental potential impacts connected with the life cycle of one non-reversible pallet with four-way blocks by applying the LCI parametric model described in Section 2.1. This type of pallet was chosen because of its significance on the market of the company, being its leading product in the market.

The LCA was conducted according to ISO 14040 standards (ISO 2006a, b), and the application of the parametric model to calculate the environmental impacts of the non-reversible four-way blocks was critically reviewed by an external expert. The function of the system is the transport of goods; the chosen functional unit, which corresponds to the reference flow, is one unit of finished pallet ready to be transported. The functional unit was defined at product level, as it does not change with the typology of the transported goods, but itself can be parameterized according to some variables such as carrying capacity. Pallets are usually designed to be used from 10 to 30 times (Gasol et al. 2008); in this case, we have assumed the lowest value as the worst-case scenario.

The process units included within the system boundaries were based on the flow scheme presented in Fig. 2. The background processes include forestry operation for wood production, as well as nails manufacture; meanwhile, the foreground processes included are all the manufacturing processes taking place inside the company. Input included inside the system boundaries are the following:

- Raw materials (wood, nails) production and use
- Auxiliary materials production and use (cardboard boxes, metallic and plastics straps, lubricating oil, labels)
- Electricity and fossil fuels consumption

Concerning the optional steps, only the high-temperature treatment and stamping phases are applicable to the product and therefore considered. Manufacturing, maintenance and dismantling of infrastructure (buildings and machineries) were excluded from the system boundaries, as well as the use of industrial soil, under the assumption that their

Table 4 Summary of the values of independent parameters for the 12 products analysed

Parameter[a]	Unit	Type of non-reversible wooden pallet with 4-way blocks											
		RP	A	B	C	D	E	F	G	H	I	L	M
l_b	m	1.200	1.200	1.200	1.200	1.200	1.200	1.000	1.200	1.200	1.200	0.900	1.200
h_deck_b	m	0.070	0.070	0.070	0.070	0.070	0.070	0.090	0.070	0.090	0.090	0.070	0.070
w_deck_b	m	0.016	0.016	0.016	0.016	0.016	0.013	0.016	0.013	0.016	0.016	0.016	0.013
h_bottom_b	m	0.070	0.070	0.070	0.070	0.090	0.070	0.090	0.070	0.090	0.090	0.070	0.070
w_bottom_b	m	0.016	0.016	0.016	0.016	0.016	0.016	0.020	0.016	0.016	0.016	0.016	0.013
n_deck_b	–	5	5	7	7	4	5	7	7	5	5	7	5
n_bottom_b	–	3	3	3	3	6	3	3	3	3	3	3	3
waste_c	–	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
rho	kg/m^3	500	500	500	500	500	500	500	500	500	500	500	500
hard_str	–	1	0.25	0.23	0.23	0.15	0.12	0	0	0.19	0.19	0	0
dist_deck_b, dist_bottom_b	km	618.9	660.9	643.3	643.3	790.4	637.3	681.8	574.6	1,029.7	1,029.7	493.2	601.5
l_bl	m	0.070	0.070	0.070	0.070	0.090	0.075	0.090	0.070	0.090	0.090	0.075	0.072
h_bl	m	0.075	0.075	0.075	0.075	0.075	0.090	0.075	0.075	0.075	0.075	0.075	0.075
dist_bl	km	464.1	463.3	464.1	464.1	401.9	396.6	401.9	464.1	401.9	401.9	387.0	411.0
l_str	m	0.800	0.800	0.800	0.800	1.000	0.800	1.000	1.000	0.800	0.800	1.000	0.800
h_str	m	0.070	0.070	0.070	0.070	0.090	0.075	0.090	0.070	0.090	0.090	0.075	0.070
w_str	m	0.016	0.016	0.016	0.016	0.020	0.014	0.020	0.016	0.016	0.016	0.017	0.013
n_str	–	3	3	3	3	3	3	3	3	3	3	3	3
dist_str	km	681.0	486.4	483.0	483.0	801.0	693.6	801.0	486.4	618.1	658.5	516.3	601.5
n_he_n	–	18	18	18	18	27	18	27	18	27	27	18	18
n_sm_n	–	24	24	36	36	36	24	36	36	24	24	36	24
mass_he_n	g	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
*mass_sm_*n	g	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.5	1.7	1.7	1.7	1.5
mass_pl_he_n	g	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
dist_nails	km	72.4	72.4	71.1	71.1	72.4	61.7	72.4	56.6	73.4	73.4	71.1	61.7
mill	–	0	0	0	0	0	0	0	0	1	1	0	0
bevel	–	0	0	1	1	1	1	1	1	1	1	1	1
HT	–	1	0	1	0	0	0	0	0	1	0	0	0
stamp	–	1	0	1	0	0	0	0	0	1	0	1	1
dist_client	km	31.8	29.4	23.9	19.0	71.5	37.6	78.8	9.5	48.9	17.1	23.0	13.2

[a] The description of the parameters is provided in Table 2

contribution to the overall environmental impact can be neglected. The output emissions into the air, water and soil deriving from the product system under study were quantified, including wastes from the manufacturing phase. With regard to cut-off criteria, which are used to decide whether processes shall be included in the product system and data gathered, a level of 2 % based on mass was applied. In other words, the process is neglected if it reaches less than 2 % of the total known mass. All processes with available data were taken into account, even if their contribution is less than 2 %. Therefore, the cut-off rule is used to avoid gathering unknown data, but not to neglect the known (Humbert et al. 2009).

2.2.2 Life cycle inventory

By applying the LCI parametric model described in Section 2.1 to the reference product, it was then possible to determine the input and output flows describing the life cycle of the non-reversible four-way blocks pallet, according to the 10 steps of the life cycle defined in Table 1. Primary data and information were obtained directly from the case study company manufacturing the wooden pallet, by means of ad hoc questionnaires developed on the basis of the 10 life cycle stages described in Table 1 and shown in Fig. 2. Secondary data were obtained from the scientific literature and databases recognized at the international level: Ecoinvent (Frischknecht

Table 5 Summary of the values of the dependent parameters for the 12 products analysed

Parameter[a]	Unit	Type of non-reversible wooden pallet with 4-way blocks											
		RP	A	B	C	D	E	F	G	H	I	L	M
w_bl	m	0.070	0.070	0.070	0.070	0.090	0.070	0.090	0.070	0.090	0.090	0.070	0.070
n_bl	–	9	9	9	9	9	9	9	9	9	9	9	9
waste_m	–	0	0	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
waste_b	–	0	0	0	0	0	0	0	0	0.002	0.002	0	0
waste_tot	–	0.03	0.03	0.035	0.035	0.035	0.035	0.035	0.035	0.037	0.037	0.035	0.035
vol_deck_b	m^3	0.00134	0.00134	0.00134	0.00134	0.00134	0.00109	0.00144	0.00109	0.00173	0.00173	0.00101	0.00109
vol_bottom_b	m^3	0.00134	0.00134	0.00134	0.00134	0.00173	0.00134	0.00180	0.00134	0.00173	0.00173	0.00101	0.00109
mass_deck_b	kg	0.672	0.672	0.672	0.672	0.672	0.546	0.720	0.546	0.864	0.864	0.504	0.546
mass_bottom_b	kg	0.672	0.672	0.672	0.672	0.864	0.672	0.900	0.672	0.864	0.864	0.504	0.546
mass_b_tot	kg	5.376	5.376	6.720	6.720	7.872	4.746	7.740	5.838	6.912	6.912	5.040	4.368
vol_bl	m^3	0.000368	0.000368	0.000368	0.000368	0.000608	0.000473	0.000608	0.000368	0.000608	0.000608	0.000394	0.000380
mass_bl	kg	0.184	0.184	0.184	0.184	0.304	0.236	0.304	0.184	0.304	0.304	0.197	0.190
mass_bl_tot	kg	1.654	1.654	1.654	1.654	2.734	2.126	2.734	1.654	2.734	2.734	1.772	1.710
vol_str	m^3	0.000896	0.000896	0.000896	0.000896	0.001800	0.000840	0.001800	0.00112	0.00115	0.00115	0.00128	0.000728
mass_str	kg	0.448	0.448	0.448	0.448	0.900	0.420	0.900	0.560	0.576	0.576	0.638	0.364
mass_str_tot	kg	1.344	1.344	1.344	1.344	2.700	1.260	2.700	1.680	1.728	1.728	1.913	1.09
n_pl_he_n	–	18	18	18	18	27	18	27	18	27	27	18	18
mass_nails	kg	0.176	0.176	0.196	0.196	0.264	0.176	0.264	0.189	0.243	0.243	0.196	0.171
mass_wood	kg	8.37	8.37	9.72	9.72	13.31	8.13	13.17	9.17	11.37	11.37	8.72	7.17
mass_pallet	kg	8.55	8.55	9.91	9.91	13.57	8.31	13.44	9.36	11.62	11.62	8.92	7.34
dist_pond	km	785.8	593.9	590.6	590.6	712.7	583.1	648.1	538.5	816.3	822.4	476.7	556.1

[a] The description of the parameters is provided in Table 3

et al. 2005), US Life Cycle Inventory (U.S. Life Cycle Inventory Database 2012) and ELCD (http://lca.jrc.ec.europa.eu/lcainfohub). The life cycle stages defined in Fig. 2 were fed into the model via parameter settings based on the collected primary data. The independent and dependent parameters with regard to the reference product are given in Tables 4 and 5 (first column), respectively. The list of the main input and output for each life cycle stage, their respective amount and datasets used are provided in Table 6. Data quality requirements refer to the criteria summarized in Table 7.

2.2.3 Life cycle impact assessment

The LCIA was performed using the Recipe 2008 methodology (Goedkoop et al. 2009) at midpoint level, focusing on a selection of impact categories:

- Climate change (CC) within a time horizon of 100 years, in kg CO_2 equivalents (kg CO2eq.)
- Fossil depletion (FD), in kg oil eq.
- Human toxicity (HT), in kg 1,4-dichlorobenzene equivalents (kg 1,4-DB eq.)

Table 6 List of the main input and output for the life cycle inventory (LCI) of the 10 life cycle stages included in the parametric LCI model. The amounts reported in the third column refer to the non-reversible four-way blocks pallet considered as reference product

No. life cycle stage	Life cycle inventory flow	Amount	Dataset
1	Softwood deck boards	1.04E−03 m^3	Sawn timber, softwood, planed, air dried, at plant/RER U
	Softwood bottom boards	1.04E−03 m^3	Sawn timber, softwood, planed, air dried, at plant/RER U
	Softwood blocks	3.79E−04 m^3	Sawn timber, softwood, planed, air-dried, at plant/RER U
	Hardwood stringer boards	9.23E−04 m^3	Sawn timber, hardwood, planed, air/kiln-dried, u=10 %, at plant/RER U
2	Steel extraction and manufacturing	9.20E−03 kg	Steel, low-alloyed, at plant/RER U + steel product manufacturing, average metal working/RER U
3	Plastic straps extraction and manufacturing	3.76E−03 kg	Nylon 66, at plant/RER U + injection molding/RER U
	Corrugated board	1.76E−04 kg	Packaging, corrugated board, mixed fibre, single wall, at plant/RER U
4	Metallic straps extraction and manufacturing	4.94E−03 kg	Steel, low-alloyed, at plant/RER U
	Lubricating oil	1.92E−03 kg	Nylon 66, at plant/RER U + injection molding/RER U
	Label manufacturing	2.05E−04 kg	Packaging, corrugated board, mixed fibre, single wall, at plant/RER U
5	Diesel for fork lifts	3.35E−03 kg	Diesel, at regional storage/RER U
	Diesel used in the boiler	1.14E−02 l	Diesel, combusted in industrial boiler/US
	Electricity (cutting phase)	8.88E−03 kWh	Electricity, hydropower, at power plant/IT U
	Electricity (assembly phase)	1.10E−01 kWh	Electricity, hydropower, at power plant/IT U
6	GPL used in the HT oven	8.82E−02 l	Liquefied petroleum gas, combusted in industrial boiler/US
	Electricity (HT treatment phase)	3.55E−02 kWh	Electricity, hydropower, at power plant/IT U
	Electricity (stamping phase)	1.01E−02 kWh	Electricity, hydropower, at power plant/IT U
7	Recycling wood waste from cutting phase to pellet	2.51E−01 kg	Recycling wood—pellet/RER U
	Cardboard to recycling	1.76E−04 kg	Recycling cardboard/RER U
	Plastic straps to recycling	3.55E−03 kg	Recycling PA66/RER U
	Labels to recycling	2.0E−04 kg	Recycling PP/RER U
	Metallic straps to recycling	4.94E−03 kg	Recycling steel and iron/RER U
8	Particulate—mg	4.9E−11 kg	Particulate emissions
9	Transport of the final product by truck	2.72E−01 tkm	Transport, lorry > 16 t, fleet average/RER U
10	Recycling of wood in the pallet	5.02 kg	Recycling wood—system expansion
	Landfill disposal of wood in the pallet	3.10 kg	Disposal, wood untreated, 20 % water, to sanitary landfill/CH U
	Incineration of wood in the pallet	2.50E−01 kg	Waste incineration of untreated wood (10.7 % water content), EU-27 S
	Recycling of nails in the pallet	1.05E−01 kg	Recycling steel and iron/RER U
	Landfill disposal of nails in the pallet	6.51E−02 kg	Disposal, steel, 0 % water, to inert material landfill/CH U
	Incineration of nails in the pallet	5.27E−03 kg	Waste incineration of ferro metals, EU-27 S

Table 7 Data quality requirements set in the collection of LCI data

Parameters	Description
Time-related coverage	2010, if secondary data are used they should not be older than 15 years
Geographical coverage	Data refer to the Italian production, but if data are not available at the national level, they refer to the average central Europe situation
Technology coverage	State of the art of wooden pallet manufacturing
Precision	Data refer to the average values at annual level mass of lower boards
Completeness	The percentage of mass inflow measured or estimated is equal to 95 %
Representativeness	The level of representativeness of data is high, as data are collected directly by the production site
Consistency	The method used for data collection, such as allocation and cut-off criteria, is consistent with the overall method
Reproducibility	The data is very specific to this study and cannot be reproduced by an independent practitioner
Uncertainty about information	The uncertainty about data and hypothesis is coherent

- Particulate matter formation (PMF), in kg PM_{10} eq.
- Agricultural land occupation (ALO), in m2a

2.2.4 Life cycle interpretation

The LCI parametric model can be used to quantify the environmental impacts of the existing different product alternatives, but can be used in product design to assess the potential impacts of future products. Possible trade-offs between the different impact categories and life cycle stages can be identified once the most influencing parameters have been identified. Based on the selection of the most influencing parameters, correlation analysis between the LCI parameters and LCIA category indicators can provide a preliminary assessment for future product design, guiding the development process towards the selection of less impacting alternatives. This procedure can be interpreted as a sort of "sensitivity analysis", where different parameters are varied in order to define their relevance on the overall final score.

3 Results

3.1 Results from the LCA of the non-reversible four-way blocks pallet

The results of the LCIA step of the reference product are reported in Fig. 3 by means of a contribution analysis (EC-JRC 2010), which shows the relative contribution of the life cycle stages to the overall impact. The absolute terms of the LCIA results are provided in Table 8 (step 3a in Fig. 1), both for the reference product and the other alternative products.

By examining the LCIA results in Fig. 3, the most relevant life cycle stages were identified, namely raw materials (wood and to a lesser extent nails) extraction and transport—positive contribution, meaning an impact; and the end-of-life—negative contribution, meaning an avoided impact. These life cycle stages refer to operations which are conducted outside the company, as they include the extraction of wood (and steel) used for pallet manufacturing. Furthermore, the contribution of transport is included, which has a relevant impact as the major part of suppliers is located in Eastern Europe. None of the operations under the direct control of the company affect more than 2 % of the overall impact for all impact categories considered, except for the high-temperature treatment, whose impact is due to fuel (liquefied gas petroleum, LPG) consumption in the industrial furnace. The corresponding most influencing input parameters are *mass_wood* (total mass of wood in the final pallet) and *dist_pond* (the weighted distance for the transport of the wood components) (step 3b in Fig. 1).

A positive contribution is due to the recycling of wood, which is responsible for about 30 % of the impact. Within the life cycle interpretation, the first step is the identification of the most relevant issues, namely the life cycle stages which are mainly responsible for the impact within each impact category, as well as the substances responsible for that impact. The results of the contribution analysis show that:

- For CC, the impact is mainly due to fossil CO_2 emissions into air originating from the transport of the wood components to the production site and from nails manufacturing. In addition, there is a contribution to a lesser extent from the combustion of LGP in the industrial furnace during the high-temperature treatment.
- For HT, the impact is mainly due to manganese emissions into water and mercury emissions into the air from electricity production during wood and nails production.
- For PMF, the impact is mainly due to NO_X and particulate (<2.5 µm) emissions into air from transport and the cutting of the wood.
- For ALO, the impact is mainly due to the occupation of forestry during wood extraction.
- For FD, the impact is due to fossil fuel used for the transport and energy production.

The main differences in the environmental impacts of the 12 pallets are due to the differences in the manufacturing processes, design and supply chain, which are correlated to the two most influencing parameters. As far as the manufacturing process is concerned, the main difference is

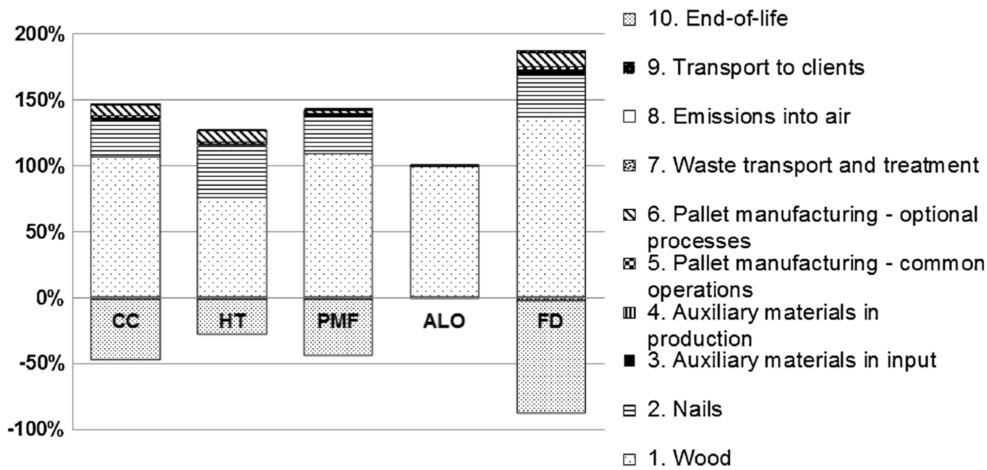

Fig. 3 Life cycle impact assessment results at midpoint level for the reference product (non-reversible four-way blocks pallet)

due to the inclusion or exclusion of the high-temperature treatment. Some of the products included in the study present the same design, but they differ only for the inclusion of the high-temperature treatment (RP and A; B and C; D and E). All the products which include the optional step present a higher impact, due to the additional electricity consumption. Concerning the design, the products with a lower mass compared with the RP, namely I and M, present a lower value for all environmental impact categories, due to the lower *mass_wood* included in the product. Those pallets with higher *mass_wood*, i.e. F, G, H and L, present a different trend according to the parameter *dist_pond*, which reflects the impact of the wood supply.

3.2 Definition of correlations between LCI parameters and LCIA category indicators

The most influencing input parameters, i.e. *mass_wood* and *dist_pond*, were determined through the contribution analysis performed on the reference product. These parameters were used to define a new parameter, commonly used in the definition of material transport in LCA, given by the product of the two previous parameters, as defined in Eq. 1, which refers to the transport of 1 tonne of goods by a certain transport service over 1 km (Spielmann et al. 2007):

$$wood\_transport[\mathrm{tkm}] = mass\_wood[\mathrm{t}] * dist\_pond[\mathrm{km}] \quad (1)$$

In order to test the relevance of these three parameters in the quantification of the environmental impact of wooden pallet, numerical correlations have been defined. Firstly, one linear parameter regression based on *wood_transport* has been tested, as well as its capability to predict the environmental impacts with a sufficient level of details (R^2>0.95).

A scatter plot of *wood transport* versus the considered impact categories is presented in Fig. 4, which refers to the outputs of step 4a in Fig. 1. As can be seen from Fig. 4, a linear correlation is suitable only for CC, PMF and FD impact categories, but not for HT and ALO. These three impact categories have a connection with the non-renewable resources depletion (GreenBlue 2009), which is involved in both the extraction and transport of wood. As the definition of a new parameter allowed a better understanding of the relationship between the most influential input parameters and impact categories indicator, therefore, a second type of regression was tested. Accordingly, the definition of correlations between input parameters and impact category indicator was carried out by considering multiple non-linear relationship in order to examine the simultaneous influence of different parameters. Three types of formula were tested to obtain the fitting equation for quantifying the relationship of environment impacts and corresponding parameters, as shown in Eqs. 2, 3 and 4:

$$y = ax_1^c x_2^d \quad (2)$$

$$y = a + bx_1 + cx_2 + dx_1x_2 + ex_1^2 + fx_2^2 \quad (3)$$

$$y = a + bx_1 + cx_2 + dx_1x_2 + ex_1^2 + fx_2^2 + gx_1^2x_2 + hx_1x_2^2 + ix_1^3 + jx_2^3 \quad (4)$$

Equation 4, being a higher degree function, appeared to be the best fitting equation, and hence can be used to predict the impact category indicator according to the variation of the two most influencing parameters, namely *mass_wood* and *dist_pond*. Usually, the more the correlation coefficients are, the better the data obtained by the correlation function fit the original data. The definition of the fitting equation was done with a Matlab code, reported in the Electronic supplementary material, based on a multiple non-linear regression (Petráš and Bednárová 2010). Furthermore, the relative error, as defined in Eq. 5, was calculated in order to test the effectiveness of the fitting equation by comparing the calculated value with the

Table 8 Life cycle impact assessment results for the 12 non-reversible wooden pallets with four-way blocks considered in the study

Impact categories	Unit	Type of non-reversible wooden pallet with 4-way blocks											
		RP	A	B	C	D	E	F	G	H	I	L	M
Climate change (CC)	kg CO_2 eq	2.27	1.84	3.08	2.86	2.29	2.11	3.02	1.90	3.17	1.8	1.79	1.57
Human toxicity (HT)	kg 1,4-DB eq	5.58E−03	4.78E−03	7.63E−03	7.39E−03	5.64E−03	5.48E−03	7.81E−03	4.91E−03	8.22E−03	4.64E−03	4.62E−03	4.03E−03
Particulate matter formation (PMF)	kg PM_{10}eq	1.07	0.90	1.36	1.26	1.12	1.02	1.33	0.91	1.39	0.86	0.89	0.76
Agricultural land occupation (ALO)	m2a	0.61	0.46	0.84	0.76	0.59	0.52	0.78	0.46	0.83	0.45	0.43	0.39
Fossil depletion (FD)	kg oil eq	68.9	57.3	73.8	74.1	66.6	66.6	72.1	50.2	83.1	49.5	47.8	39.2

actual value given by the implementation of the LCI parametric model.

$$\text{Relative Error} = \frac{|\text{Actual Value} - \text{Calculated Value}|}{\text{Actual Value}} \qquad (5)$$

The value of the relative error was used to define the cut-off for the ability of the correlation function to predict the actual value, which was set equal to 5 % for each data point. In Table 9, the coefficients of the fitting equation are reported according to the impact category indicators considered in this study. The calculation of the impact category indicators according to the fitting equation and the calculated values, as well as the relative errors, is further detailed in the Electronic supplementary material. The definition of such correlations allowed for predicting the environmental impacts of new products according to the selected value of the primary parameters (step 4b, Fig. 1).

4 Discussion

From a company's point of view, there is a need for streamlined (or "simplified") approaches to shorten the lengthy and resource-consuming environmental assessment process. In practice, a full-scale LCA can be both time and resource intensive and this leads to outcomes that are not always the primary or best action for a company trying to develop its processes or products towards a more sustainable direction. In fact, the inherent complexity of carrying out a full LCA can be hypothesized as standing in the way of a widespread application in the industry and policy-making sectors (Bala et al. 2010). Furthermore, the results of a full LCA can be very complex and difficult to understand for decision-makers both in the industry and the public sector. Therefore, the development of simplified tools has been widely encouraged (Zamagni et al. 2012). However, despite the consistent number of simplified LCA techniques based both on qualitative, quantitative and semi-quantitative approaches, we should not neglect the relevance of integrating these techniques with proper assessment of the reliability of LCA results (Niero 2013b). Furthermore, companies should be aware that the results of screening LCA cannot be used in the case of comparative assertions disclosed to the public.

The present study focused on the definition of a LCI parametric model in order to calculate inventory data from the quantification of parameters describing the life cycle of a generic wooden pallet. The identified parameters refer to the technical characteristics of the product system, e.g. the number and dimension of elements constituting the wooden pallet, as well as aspects of the manufacturing process, e.g. inclusion of optional steps. The parameters were divided into two categories: independent and dependent parameters. The

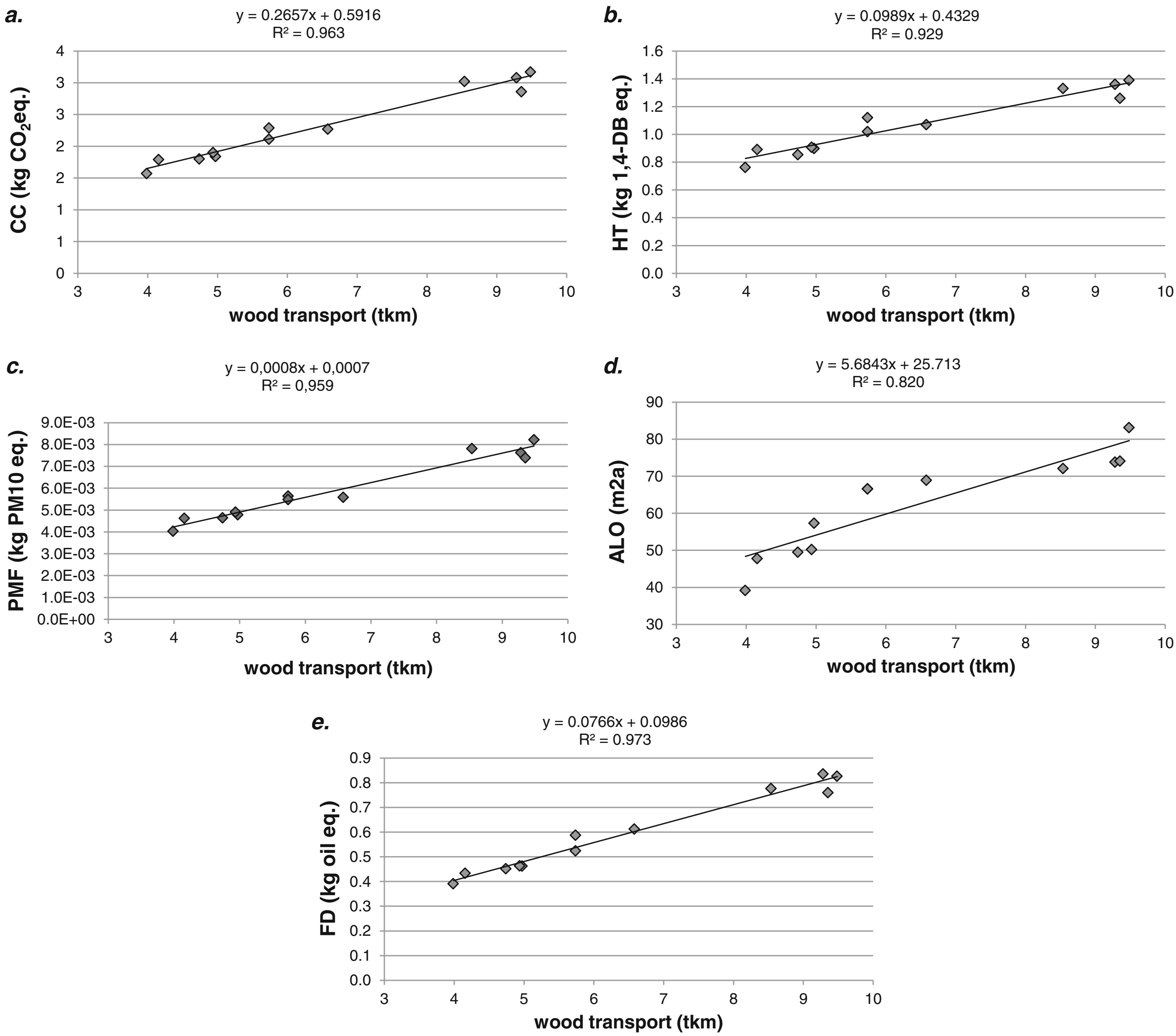

Fig. 4 Linear regressions for wood transport versus **a** climate change (CC), **b** human toxicity (HT), **c** particulate matter formation (PMF), **d** agricultural land occupation (ALO) and **e** fossil depletion (FD)

Table 9 Coefficients of the selected fitting equation (Eq. 4) with multiple regression for the impact category indicators: climate change (CC), particulate matter formation (PMF), human toxicity (HT), fossil depletion (DF), agricultural land occupation (ALO)

Coefficients of the fitting Eq. 4	Life cycle impact category				
	CC	PMF	HT	FD	ALO
a	93.5412	0.1061	61.6127	30.6272	2631.6
b	11.8064	−0.0110	−7.7428	−3.8059	−194.3
c	−0.2645	−0.0003	−0.1753	−0.0881	−10.2
d	0.0320	0	0.0212	0.0102	0.5
e	0.1857	0.0003	0.1158	0.0640	5.5
f	0.0002	0	0.0001	0.0001	0
g	−0.0004	0	−0.0002	−0.0001	0
h	0	0	0	0	0
i	0	0	−0.0006	0.0001	−0.0002
j	0	0	0	0	0

definition of a LCI parametric model based on 31 independent parameters and 21 dependent parameters can speed up the data collection process, as the information required for fulfilling the LCI are standard information about the features of the wooden pallet and the manufacturing process, easily accessible by the company. The focus in the definition of the functional unit has been at the product level; it indeed refers to "one unit of finished pallet ready to be transported" rather than on the capacity of the pallet to transport a specified amount of goods for a defined period of time. But since the amount of goods that can be transported with a pallet strongly depends on the size of the pallet and its lifespan can be increased through more intensive treatment within the manufacturing stage, the LCI parametric model should be preferably applied to compare wooden pallets with the same characteristics, therefore providing the same function.

The LCI parametric model was tested with one reference product, namely one non-reversible pallet with four-way blocks manufactured by the case study company. The input and output flows were quantified according to 10 life cycle stages. By examining the results of the contribution analysis, the most relevant life cycle stages were identified: raw materials (wood and nails) extraction and transport and the end-of-life. These results are consistent with what has been obtained by similar studies on wooden containers (Gasol et al. 2008; Anil et al. 2010) and wooden pallets (Dotelli 2011). Furthermore, the primary parameters influencing each impact category were also identified as follows: *mass_wood* (the total mass of wood in the pallet) and *dist_pond* (the weighted distance for the transport of the wood components). An additional parameter was defined, i.e. *wood_transport* (the averaged transport of the wood, given by the product of *mass_wood* and *dist_pond*, which is the weighted distance for the transport of the wood components).

Once the most influencing parameters were detected, it was then possible to apply the LCI parametric model to further 11 products selected by the case study company and belonging to the same category, namely non-reversible four-way blocks pallets. The developed LCI parametric model can be directly used to calculate the potential environmental impacts of any other products manufactured by the case study company, for which a complete set of independent and dependent parameters can be defined. This means that from a company's perspective, each product can be accompanied by a sort of "environmental identity card", which can help the consumer/supplier to choose among different solutions, adding the environmental criteria in the decision process.

The application of the LCI parametric model to a range of 12 products helped to further streamline the integration of LCA in the decision-making process at the company level. It was indeed possible to define mathematical correlations between the most influencing LCI parameters and the corresponding impact category score. The correlation was defined both with one parameter regression and multiple non-linear regressions. From the one parameter regression, it emerged that for impact categories that are predominantly related to the non-renewable resources depletion, i.e. climate change, fossil fuels depletion and particulate matter (GreenBlue 2009), a linear correlation can be defined by taking into account the new defined parameter *wood_transport*. As far as the multiple non-linear correlation is concerned, different types of formulas have been tested, and the final version was defined by calculating the relative error. In both cases, the criteria to assess the ability of the correlation function to estimate the impacts was defined by cut-off criteria (i.e. coefficient of regression and relative error). The definition of mathematical correlation between inventory data and environmental impacts can be used to inform product designers and developers at an early stage of the design process. In fact, the impact of a new product with a defined amount of mass wood and/or a specific supply of wood can be estimated by the correlations, which provide a rough quantification of the environmental impacts before starting a full LCA application, revealing the potential of the LCI parametric model as a preliminary environmental assessment tool. The use of correlations can be seen as an extended form of sensitivity analysis, where the most impacting parameters and therefore life cycle stages are screened and used to optimize the design of new products. The following step is the implementation of the LCI parametric model which allows calculating the precise value of the environmental impacts of the new products. Different from having a database of LCA inventory information that can be reused for future projects, the definition of a LCI parametric model has the advantage of flexibility. It can indeed be easily modified to consider changes in the design of the wooden pallet: if the value of one independent parameter is changed, consequently, the values of dependent parameters are modified accordingly, therefore saving time in the collection of LCI data. This modelling approach can be replicated in the wood pallet sector as well as in other manufacturing sectors, provided the products being examined present similar characteristics. If the products manufactured by the company are very different, then it might be more useful to have a database of LCA inventory information to be updated according to the design need.

5 Conclusions

Conducting LCA studies is time consuming and requires a lot of effort for data collection and modelling. As in the future development of the wooden packaging system, it will be necessary to integrate LCA in the design process; therefore, it is important to define some ways of simplifying its application and spread its use among companies. In this research, we considered a single case study based on an Italian company in

order to investigate to what extent companies in the wooden pallet sector can benefit from the use of parametric LCI models for calculating the environmental impacts of similar products and evaluating the environmental impacts of new products before their launching into the market. The defined general LCI model is based on 31 independent parameters and 21 dependent parameters, which refer mainly to the physical characteristics of a wooden pallet, i.e. the number of constituting elements, size, transport and inclusion of optional processes in the manufacturing phase.

The conceptual scheme described in the paper can be applied by any manufacturing of the wooden pallet; meanwhile, the specific LCI parametric model is tailored to the case study company. This model can be easily applied to calculate the inventory flows of other non-reversible four-way blocks wooden pallets manufactured by the case study company, confirming the predictability of LCI flows by defining appropriate technical parameters. SMEs in the wooden pallet sector can benefit from the use of a parameterized LCI model based on the definition of a general model that can easily be adapted to the collection of LCI data for any specific company.

The second application focused on the use of the LCI parametric model to calculate the environmental impacts of a reference product manufactured by the case study company, i.e. a non-reversible four-way blocks pallet, with regard to a selection of impact categories (climate change, particulate matter formation, human toxicity, agricultural land occupation and fossil depletion). Based on the contribution analysis, the most relevant life cycle stages were identified, namely raw materials (wood and to a lesser extent nails) extraction and transport and the end-of-life. The results were confirmed by other LCA studies in the wooden packaging literature and this proved the effectiveness of the LCI parametric model to predict the environmental impacts of a wooden pallet.

Finally, once the most influencing parameters were detected through the contribution analysis, the LCI parametric model was applied to further 11 wooden pallets with similar characteristics. This enabled the estimation of correlations between the most influencing LCI parameters (*mass_wood*, *dist_pond* and a new parameter, given by the product of the two previous ones—*wood_transport*). The numerical correlations were defined with both one parameter linear regression and multiple non-linear regression. The definition of the mathematical correlations between inventory data and environmental impacts can be used to support product design and development. In fact, the environmental impacts of a new product with a defined amount of mass wood and/or a specific supply of wood can be calculated by the correlations, which provide a rough quantification of its environmental performances before starting a full LCA application. However, it should be mentioned that the correlation analysis is based on a limited number of data points. The main purpose of using the correlation function is to propose a generic methodology, and it may be more suitable for other case studies concerning LCI with more data points. Another limitation of the defined LCI parametric model is its lack in addressing changes in the functional unit definition, i.e. including the life span aspect or possible changes in the amount of transported good. This aspect could be addressed extending the scope of the study and defining other parameters able to account for the different number of uses of the wooden pallet, e.g. including the maintenance phase among the life cycle stages. Our recommendation is therefore to apply the LCI parametric model described in the paper to compare wooden pallets with the same characteristics, in order to avoid biased comparisons.

Within the wood sector, additional research is also required to investigate the influence of forest management on the final outcomes of an LCA study, as proposed by Michelsen (2007) with regard to the impacts on biodiversity. Further investigation is also needed in order to define specific guidelines that can help in the selection of the most suitable LCIA categories for screening LCAs according not only to the objectives and purpose of the study, but also according to the industrial sector.

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